

The Vapor Pressure of Motor Fuels and Their Tendency to Vapor Lock

By

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Motor-Fuel Volatility¹

V—Vapor Pressure and Vapor Lock^{2,3}

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THE practical advantages in the use of fuels having low 10, 35, and 65 per cent points on the A. S. T. M. distillation curve have been indicated in Part IV. The fuel systems of many motor cars, however, are so constructed that in warm weather the temperature of the liquid gasoline frequently reaches 135° to 140° F. and may in some cases exceed 200° F. This fact places a minimum on the temperature of the 10 per cent point in order to insure that the fuel does not vaporize before reaching the manifold.

It is, of course, impossible to prepare a fuel that will form sufficient vapor to start the motor readily at 10° F. and yet will not vaporize in the fuel line and carburetor when heated to a temperature in excess of 130° F. Yet this is one of the demands made upon motor fuel by some of the modern passenger cars.

Formation of fuel vapor in those passages designed to carry, or meter, liquid fuel causes what is commonly called "vapor lock." Since the volume of gasoline vapor is approximately 185 times that of an equal weight of liquid fuel, it is obviously impossible for the small orifices and passages in the carburetor to pass enough gasoline vapor to maintain an explosive mixture. A relatively small amount of vapor, usually not in excess of about four times the liquid volume, will usually so limit the flow of gasoline to the manifold that

¹ The investigations reported in this series of papers have been carried out during the past four years in the Chemical Engineering Laboratory of the University of Michigan. Owing to the interdependence of various phases of the work, publication of the results has been delayed. More complete information than can be given in this series of papers will be found in *Bulletin 14* of the Department of Engineering Research of the University of Michigan, available in the near future.

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³ Part of a thesis submitted by E. A. Clarke in partial fulfillment of the requirements for the degree of doctor of philosophy at the University of Michigan.

the motor will not perform properly. Any further vaporization of the fuel in the liquid lines or jet of the carburetor restricts the flow of gasoline so that the mixture supplied to the motor becomes non-explosive.

The obvious remedy of this difficulty is so to design the fuel system of the motor car that the liquid fuel receives the minimum amount of heat from the motor. Many manufacturers have, however, been extremely careless in this regard and have placed the fuel line leading from the supply tank adjacent to the muffler and exhaust pipe of the engine. In many cases gasoline is further heated by conduction of heat from the hot crankcase on which the mechanical pump is mounted. If the fuel has not been heated to sufficiently high temperatures to vaporize by this time, it is still further

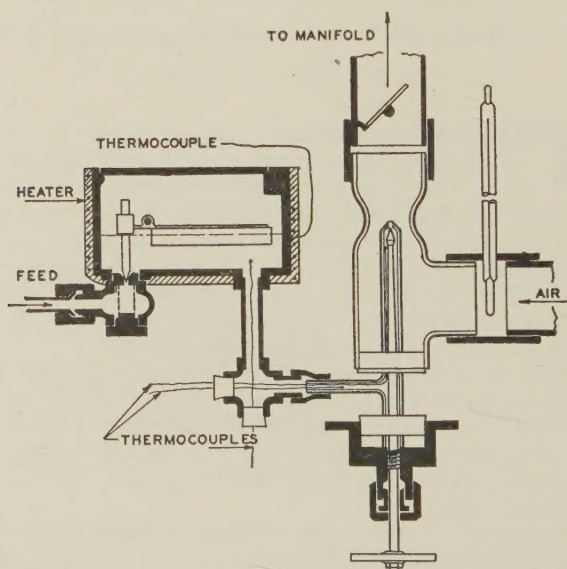


Figure 1—Cross Section of Glass Carburetor and Standard Bowl Used in Laboratory Tests for Vapor Lock

heated in the carburetor by conduction of the exhaust heat from the hot spot or convection from the adjacent exhaust manifold. When it is considered that the fuel is under a slight vacuum from the supply tank to the pump fuel, it is not surprising that vapor lock is frequently encountered in the fuel pump as well as in the carburetor.

As long as such cars are on the road, suitable fuel must be available for their satisfactory operation. For this reason the following investigation was undertaken to ascertain, first, that property or characteristic of the fuel which indicates or determines its tendency to cause vapor lock; and secondly, the practical limits necessary to observe in order to insure satisfactory operation on modern automotive equipment.

Tendency of Fuel to Vapor Lock

The liability of a fuel to cause vapor lock is dependent on the tendency of that fuel to form vapor. A liquid will tend to form vapor in direct proportion to its vapor pressure. For these reasons the vapor pressure of the fuel must bear some relationship to its tendency to cause vapor lock. As has been pointed out (2), vapor pressure, or the tendency to form vapor, must not be confused with volatility, which is the extent to which the fuel will vaporize under specified conditions. Volatility is the extensive factor in the vaporization of fuels, and has been definitely related to engine performance in the previous papers of this series. Vapor pressure, on the other hand, is the intensive factor in the vaporization of fuels and its relation to vapor lock will be demonstrated. High volatility is a desirable characteristic to insure easy starting and satisfactory motor performance, but high vapor pressure is to be avoided in order to insure freedom from vapor lock.

ROAD TESTS—Early attempts to estimate the tendency of fuels to vapor lock from laboratory vapor-pressure measurements proved unsuccessful because of inadequate information concerning the behavior of fuels under actual driving conditions.

Apparatus. A passenger car was especially equipped with auxiliary fuel tanks, pressure- and vacuum-feed systems, and the necessary instruments to obtain adequate information concerning the temperature of the fuel. The type of car equipped with an 8-cylinder, V-type motor with the carburetor mounted between the V and the two exhaust manifolds was chosen because it is one of the worst offenders in regard to vapor lock and illustrates the extreme conditions encountered in service. Each of the six auxiliary fuel tanks had a capacity of approximately 8 gallons, which was sufficient for a test of at least one hour's duration. The fuel was fed from the bottom of the tanks, which were built with a slope so as to drain completely, through valves in a manifold under the rear seat. These valves were so arranged that it was possible to feed any one of the six fuels to the carburetor through either the vacuum tank or fuel pump. It was possible to change the fuel supply while the car was being operated under constant driving conditions, in order to make a direct comparison between fuels of different characteristics.

A gas thermometer was mounted with its bulb on the cross member in front of the radiator and its dial on the dash for measuring the outside or atmospheric temperature. A mercury dial thermometer was similarly arranged to indicate the temperature of the air under the hood between the V of the engine blocks and the exhaust manifolds at the intake of the carburetor. Thermocouples were placed in the vacuum tank, in the fuel line between the three-way cock and the carburetor, in the bowl of the carburetor, in the duct leading

from the bowl to the jet, in the tip of the main jet, and in the intake manifold. The cold junctions were assembled in a junction box the temperature of which was indicated by a mercury-in-glass thermometer. These temperatures were determined by a portable potentiometer operated by an observer in the rear seat.

Procedure. A driver and at least two observers are required for satisfactory testing of fuels on the road. One of the observers is kept busy reading the temperatures of the thermocouples as indicated on the portable potentiometer. The second observer records the temperatures as read by the first observer and those indicated by the thermometers mounted on the dash, and also sees to proper operation of the fuel valves if a third observer is not available.

The fuels were placed in appropriate tanks. The car was driven at a speed of about 40 to 50 miles an hour until all temperatures became practically constant to warm up the motor to represent driving conditions. The first fuel to be tested was then fed directly to the carburetor under pressure and the car driven at maximum speed until temperatures became constant. All temperatures were recorded and notes were made as to whether or not any trouble due to vapor-locking was experienced. If vapor-locking occurred the lowest temperature at which it was first observed was noted as well as the highest temperature at which the car could be driven without noticeable trouble. The car was then stopped for 8 or 9 minutes to allow the gasoline in the carburetor to reach the maximum temperature.

After a period of hard driving the manifolds become heated, and this heat flows down into the carburetor through the metal and is radiated to the carburetor from the hot exhaust manifolds after the car has stopped. When driving, the flow of gasoline through the carburetor and the vaporization of the gasoline in the manifold tend to cool the carburetor to lower temperatures.

While the car was stopped gasoline and air temperatures were carefully observed. If vapor lock occurred in the carburetor, there was usually a drop in the temperature of the gasoline in the jet passage, or bowl, caused by vaporization of the gasoline. After the gasoline had reached the maximum temperature, an attempt was made to start the car, and the behavior and temperatures were recorded.

This procedure was repeated in order to obtain check results. Usually no particular difficulty was experienced in checking results obtained when the gasoline was fed to the carburetor under pressure.

The car was then again driven at high speed for 8 to 10 minutes, when a test for vapor lock was made by retarding speed to 20 miles per hour, instead of stopping. The vacuum tank was then drained and the same fuel fed to the carburetor through the vacuum tank under similar conditions of test. When feeding the fuel through the vacuum tank, it was fre-

quently very difficult, if not impossible, to obtain check readings unless the vacuum tank was drained after every stopping period.

These tests were conducted over a period of about 3 years. Atmospheric temperatures from -20° to 90° F. were em-

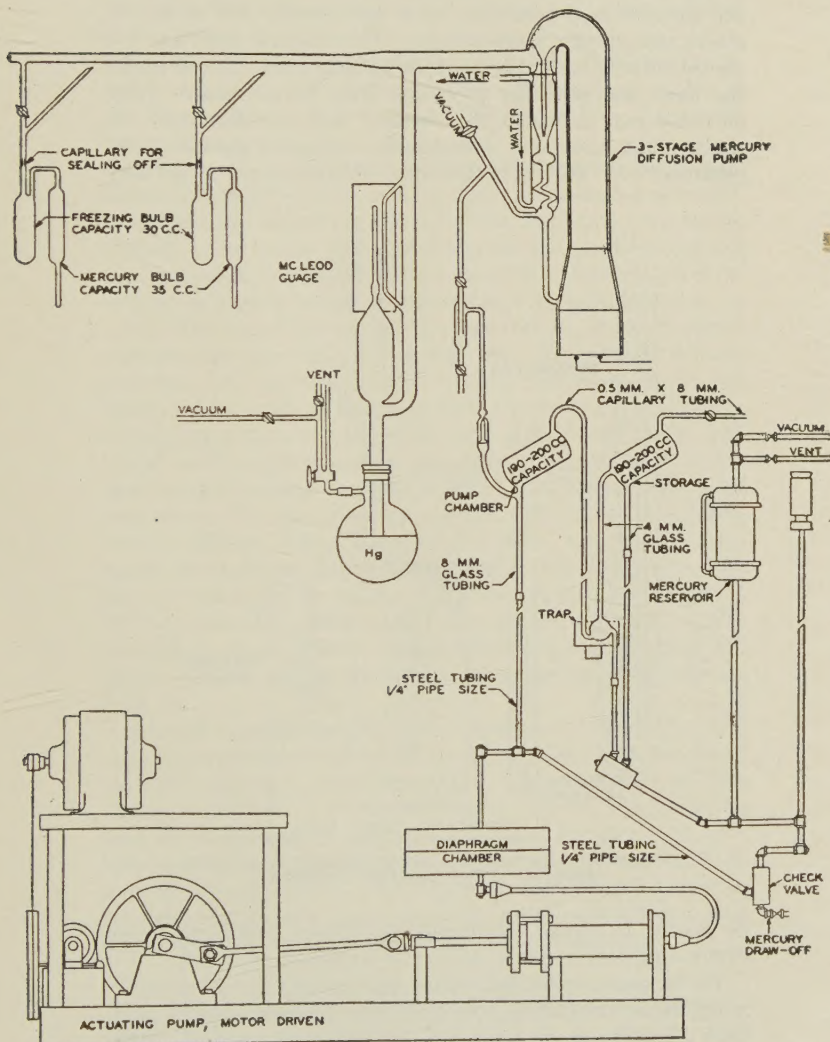


Figure 2—Diagram of Apparatus Used to Pump Off Dissolved Gases from Samples of Dried Fuel

ployed and all types of motor and aviation fuels were used.

Results. Fuels which would not properly perform when fed through the vacuum tank could frequently be used to operate the car at high speed without any vapor lock when fed through the pressure-feed system. This fact is partially

explained by a comparison of the temperature of the gasoline in the carburetor under the two different conditions of tests. Frequently the temperature of the gasoline when fed through the vacuum tank was about 35°F. higher than when fed to the carburetor under pressure feed. The temperature of the gasoline in the vacuum tank was usually 30° or 40°F. above atmospheric temperature. This vacuum tank was not placed entirely under the hood, but a large part of it was under the dash and partially protected from motor heat. Tests on other cars in which the vacuum tank was mounted entirely under the hood occasionally indicated gasoline temperatures over 180°F. in the tank. Furthermore, a fuel may

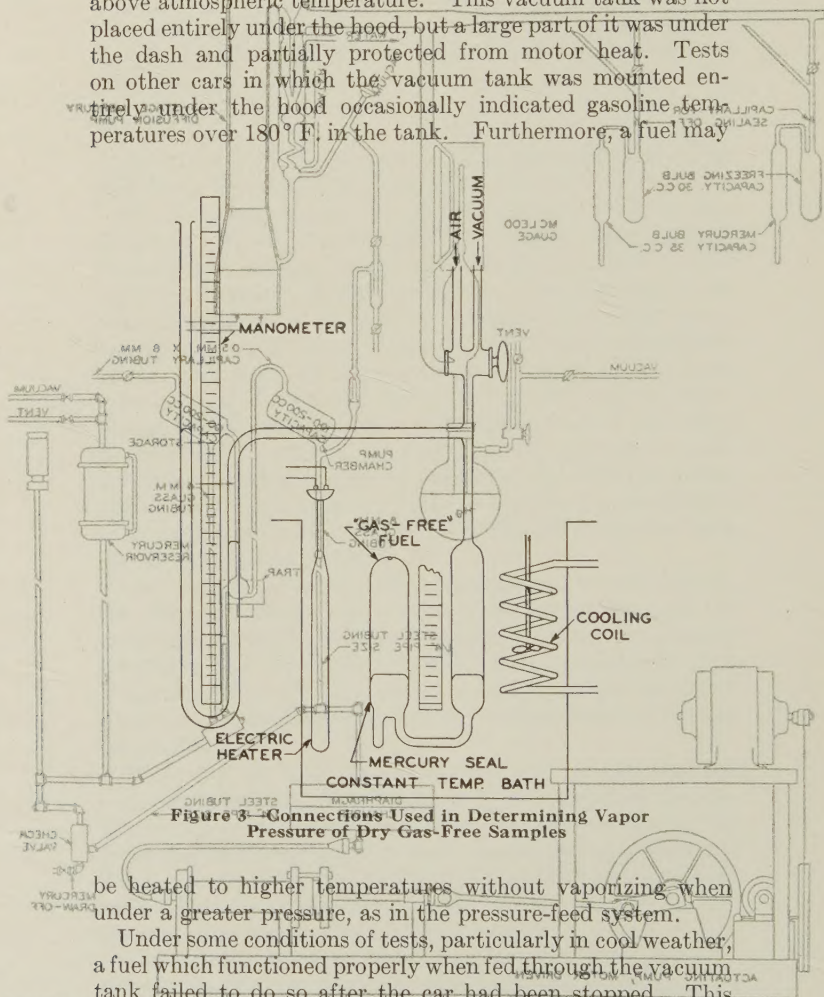


Figure 3—Connections Used in Determining Vapor Pressure of Dry Gas-Free Samples

be heated to higher temperatures without vaporizing when under a greater pressure, as in the pressure-feed system.

Under some conditions of tests, particularly in cool weather, a fuel which functioned properly when fed through the vacuum tank failed to do so after the car had been stopped. This was puzzling at first. Continued testing led to the conclusion that the gasoline in the vacuum tank absorbed the more volatile material vaporized in the gasoline line leading from the vacuum tank to the carburetor during these periods in which the car was stopped after hard driving. Under these conditions bubbles passing up through the fuel line into the vacuum tank were clearly audible to observers in the car. Fuel drained from the vacuum tank after such experiences

possessed a higher vapor pressure than fuel drained from the supply tank at the rear of the car.

LABORATORY TESTS.—The road tests were necessary to determine temperature conditions on motor cars under actual driving conditions. But the correlation of the test data proved rather unsatisfactory in a number of cases because of the many uncontrollable variables. A glass carburetor was therefore constructed and operated in the laboratory under carefully controlled conditions in order to make it possible to observe in detail the actual formation of vapor in the carburetor.

Equipment. An L-head, 6-cylinder motor with the intake manifold heated by the exhaust gases was direct-connected to an electric dynamometer for load variation and speed control. The motor was equipped with the glass carburetor constructed as shown in Figure 1 in order to make it possible to observe exactly what happens when a fuel vapor locks.

The Venturi of the carburetor was formed of Pyrex glass, as were also the fuel passage and jet. The standard float chamber was surrounded by electric resistance wires for heating the bowl to any desired temperature. Thermocouples were placed in the metal wall of the bowl, in the fuel in the bowl, in the passage, and just below the jet in positions corresponding to those in the carburetor used in the road tests. The fuel passage and jet were formed of Pyrex tubing with an inside diameter of 6 mm., and the jet was drawn down to an inside diameter of 2 mm., forming a seat for the brass needle valve for controlling the air-fuel ratio delivered by the carburetor. The air supply was drawn through an electric heater with sufficient capacity to heat the air to 450° F., when the motor was running at maximum load.

Procedure. The motor was operated at 600 and 1200 r.p.m., corresponding to about 12 and 25 miles per hour with the throttle about two-thirds open and the cooling water at 160–165° F. Under these conditions the temperature of the gasoline in the bowl was raised by passing a controlled amount of electrical energy through the heating coils surrounding the bowl. The action of the fuel as it passed through the jet was determined by visual observation and temperatures of the fuel were recorded as follows:

- (1) When bubbles first appeared in the fuel stream.
- (2) When the vapor bubbles became sufficiently large to affect the running of the motor.
- (3) When the motor stopped.
- (4) When boiling of the gasoline in the bowl of the carburetor occurred.

In the road tests the air temperature under driving conditions frequently reached 200° F. For this reason, in the laboratory, usually two series of tests were run with air temperatures of 165° and 205° F. Other series at lower and higher speeds are also run to determine the effect of speed on

Results. When extremely hot air (about 250° F.) was supplied to the carburetor, the gasoline in the jet passage could be made to vaporize even when not heated in the bowl of the carburetor. When the bowl of the carburetor was heated, small bubbles first collected on the surface of the metal, where the gasoline was heated to the higher temperatures. If the motor was being driven at relatively high speed, the flow of fuel through the passage out of the bowl exerted sufficient force to remove these small bubbles from the surface of the bowl and carry them through the needle valve and jet with the liquid fuel without forming sufficiently large bubbles to cause uneven running of the motor.

Under the same temperature conditions, if the motor was operating at low speed the force exerted by the gasoline flowing through the passages and needle valve was not sufficient to remove these small bubbles from the heated metal surface, and the bubbles continued to grow until they became so large, before being swept away, as to block the passage, causing uneven running of the motor or entirely interrupting its operation.

Some fuels seem to give off vapor so rapidly that the bubbles do not cling to the heated metal surface but pass up out of the bowl. This action, known as boiling in the bowl, frequently occurs without any apparent effect on the running of the motor. In fact, with some fuels this so reduces the vapor pressure of the fuel flowing through the passages that higher fuel temperatures in the jet passage may be used without any evidences of vapor lock when the fuel is boiling in the bowl than when this condition does not obtain.

Bubbles forming in the passages of the carburetor are subject to the same conditions as bubbles forming in the bowl. Operation of the motor at low speed does not give the fuel sufficient velocity through the passage to carry the small bubbles through the jet, but allows the bubbles to grow in size until they become so large as to cause uneven running of the motor.

The jet, and jet passage are heated by two sources—conduction through the metal, and from direct contact with the hot air drawn into the carburetor. The formation of bubbles in the jet passage is probably the most important cause of vapor lock in the carburetor. The main fuel passage in the carburetor is of sufficient diameter to pass enough fuel for satisfactory operation of the motor, even when relatively large volumes of vapor are flowing through these passages with the liquid. The small opening of the jet itself, however, is usually inadequate to pass sufficient weight of fuel if much more than half the total volume of the fuel flowing through the jet is in the vapor state.

As the temperature of the air supplied to the carburetor is generally higher than that of the fuel supplied to the jet, fuel flowing through the jet passage is usually heated to its maximum temperature just under the jet. This condition

also makes the jet passage the most likely place for the formation of the greatest volume of vapor from the fuel. Small bubbles flowing through the passages of the carburetor generally expand in the jet passage owing to the heating effect of the hot air supplied to the carburetor and also owing to the slight decrease in pressure existing in the jet passage. This is emphasized in many carburetors by bleeding air into the jet passage, thereby decreasing the partial pressure of gasoline vapor so that more gasoline tends to vaporize, still further decreasing the fuel flow.

If these expanding bubbles in the jet passage become so large as to fill the cross section of the passage, the flow of liquid gasoline to the jet is interrupted. This irregular flow of gasoline causes uneven operation of the motor. As long as the volume of the bubbles does not exceed approximately that of the liquid gasoline, the motor will operate in a satisfactory manner with only a negligible loss in power.

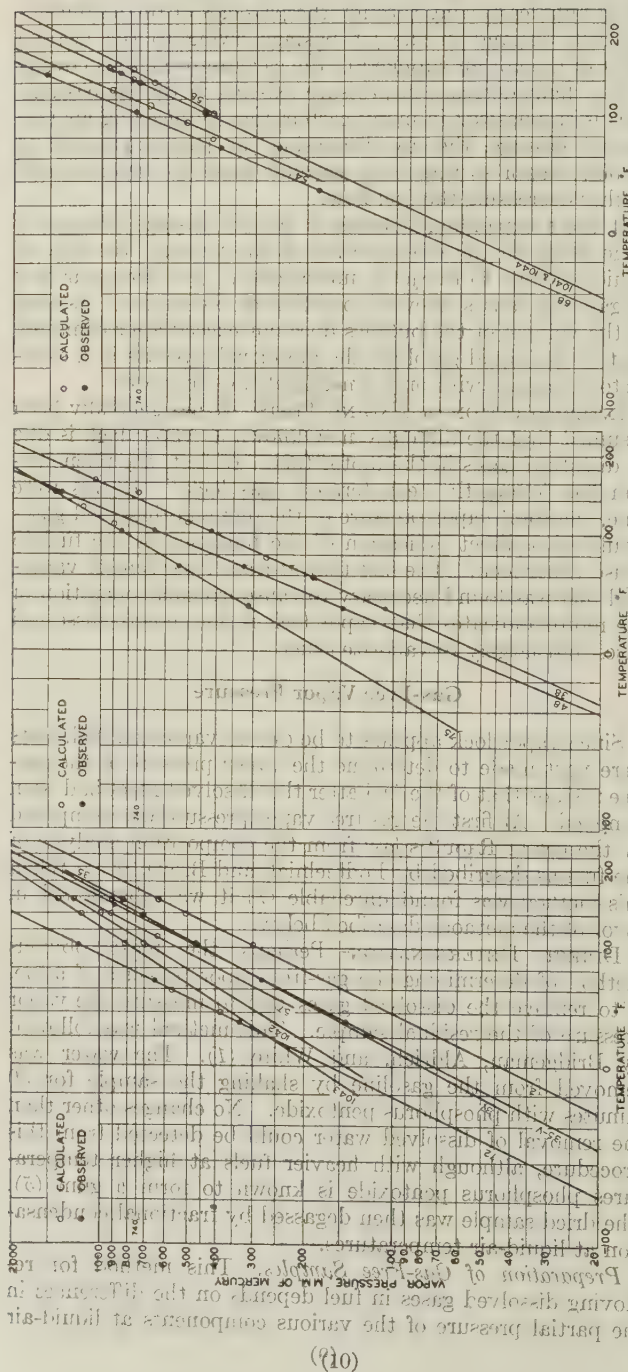
INTERPRETATION OF ENGINE TESTS—It has generally been assumed that the difficulty now known as vapor lock is due to dissolved gases in the motor fuel. In fact, the phenomenon has frequently been termed "gas lock." If this were true, the total vapor pressure of the fuel and dissolved gases would be a direct indication of the tendency of the fuel to cause vapor lock. The fact that at least 1 per cent of vaporized fuel was found necessary to cause irregular operation of the motor indicates that vapor lock is due, not to dissolved gases, but largely to vaporized fuel.

Gas-Free Vapor Pressure

Since vapor lock appears to be due to vaporized fuel, tests were next made to determine the vapor pressure of the gas-free fuel, or that of the fuel after the dissolved gases had been removed. At first the gas-free vapor pressure was computed by the use of Raoult's law from the composition analysis of the fuel as described by Podbielniak and Brown (6). When this method was found unreliable (?) it was abandoned in favor of the methods described below.

DIRECT DETERMINATION—Perhaps the most obvious method of determining the gas-free vapor pressure of a fuel is to remove the dissolved gases and to measure the vapor pressure of the residual sample. This method was followed by Bridgeman, Aldrich, and White (1). The water was removed from the gasoline by shaking the sample for 30 minutes with phosphorus pentoxide. No changes other than the removal of dissolved water could be detected from this procedure, although with heavier fuels at higher temperatures phosphorus pentoxide is known to form a gum (5). The dried sample was then degassed by fractional condensation at liquid-air temperatures.

Preparation of Gas-Free Samples. This method for removing dissolved gases in fuel depends on the differences in the partial pressure of the various components at liquid-air



Figures 4-A, B, C—Log of Vapor Pressure of Dry, Gas-Free Fuels Plotted against Reciprocal of Absolute Temperature

The solid points are those given in Table I, and the open circles represent data given in Table II

temperatures. Hydrocarbons with three carbon atoms or more are not considered gases. At liquid-air temperatures oxygen, nitrogen, and argon have vapor pressures approximately equal to 1 atmosphere, methane from 20 to 70 mm., ethane and ethylene about 0.1 mm., acetylene greater than that of ethane and less than that of methane, and carbon dioxide and propane 0.001 mm. or less. The sample was frozen at the temperature of liquid air. The gases left in the vapor phase were then pumped off until the pressure was reduced to less than 0.001 mm. The sample was then warmed to approximately room temperature to release dissolved gases and some vapor. This cycle was repeated by again freezing the sample and pumping to a pressure of 0.001 mm., and continued until the residual pressure after freezing and before pumping did not exceed 0.0015 mm.

By this process all the dissolved gases except carbon dioxide were, for all practical purposes, completely removed, with removal of only a negligible quantity of propane. Fortunately, the carbon dioxide content of commercial gasoline is negligible and no special procedure for its removal was found necessary.

Table I—Vapor Pressure of Dry, Gas-Free Fuels as Determined Directly in Apparatus

FUEL	TEMPERATURE		VAPOR PRESSURE			
			BUBBLE		Average	
			In	Out		
	° C.	° F.	Mm.	Mm.	Mm.	
35a	0.2	32.36	140	140	143	
	20.0	68	274	274	277	
	40	104	457	457	461	
	65	149	880	878	881	
38	0.4	32.7	102	103	106	
	20	68	221	221	222	
	40	104	410	410	412	
	65	149	831	831	834	
48	0.25	32.4	146	147	149	
	20	68	318	318	323	
	40	104	652	654	655	
	65	149	1331	1331	1334	
68	0.3	32.54	180	179	182	
	20	68	394	392	395	
	40	104	758	758	761	
	65	149	1539	1539	1542	
72	1	33	331	331	332	
	20	68	644	644	647	
	40	104	1176	1176	1179	
	65	149	2308	2308	2311	
75	0.3	32.5	308	308	311	
	20	68	585	586	588	
	40	104	834	833	837	
	65	149	1440	1442	1445	
104A	20	68	245	245	248	
	40	104	441	441	444	
	65	149	867	867	865	

a Sample taken from vacuum tank after absorbing vapor from fuel line to carburetor.

The apparatus shown in Figure 2 was so constructed that the gases removed from the sample could be collected and identified. Except for this feature and the elimination of mercury-sealed valves, the construction of the apparatus is essentially the same as that described by Bridgeman, Aldrich,

and White (1). The mercury-sealed valves were found unnecessary for satisfactory operation. Furthermore, the vapor pressure of the mercury at room temperature is about the same as that to which the samples were exhausted, and seriously interfered with efficient pumping, particularly in warm weather. For this reason 5-mm. glass cocks were found more satisfactory.

The three-stage mercury diffusion pump was provided with connections so that it could be supported or backed by a laboratory vacuum pump or the Toepler displacement pump shown in the figure. By use of the Toepler pump the gases removed from the sample are automatically collected over mercury and can be removed for analysis. The diaphragm chambers have a total volume of about 250 cc. and are divided by a rubber diaphragm; the upper side is filled with mercury and connected to the Toepler bulb, and the lower, filled with water, is connected to the mechanical actuating pump.

The actuating plunger pump is without valves, so that the movement of the diaphragms follows directly the movement of the plungers. The stroke of the mechanical actuating pump can be adjusted so that just the proper amount of mercury is forced out of the diaphragm chamber to fill the Toepler bulb and the discharge capillary tube to the trap. The actuating pump was driven at such a rate that a complete cycle took 54 seconds.

Procedure. Samples prepared in this way were sealed off in the U-tube and confined over mercury in the upright position. A manometer was then connected to the other side of the U-tube and the vapor pressure of the gas-free sample determined for different temperatures in the apparatus shown in Figure 3. The three-way stopcock was used to adjust the air pressure between the mercury surfaces in the U-tube and in the manometer by making connections either to the vacuum line or to the atmosphere. In making a determination of vapor pressure, the temperature of the sample was maintained constant in a thermostat, and the pressure on the gasoline reduced by operation of the three-way cock until vapor formed above the liquid sample. Liquid hydrocarbons are readily superheated if not agitated, and careful manipulation was required to avoid sudden formation of a large volume of liquid which would force part of the sample past the mercury seal in the U-tube. As soon as vapor phase appeared the pressure was rapidly adjusted until only a small bubble of vapor remained in the tip of the tube. Readings of the mercury level in the manometer were then taken with minor adjustments in pressure to maintain the bubble just slightly larger than the head of a pin. After a few minutes the pressure could be maintained constant within 1 mm. under these conditions. The final reading was then recorded as the vapor pressure of the gas-free sample at the temperature of the bath. A slight increase in

pressure was sufficient to cause the bubbles to disappear entirely.

Results. The gas-free vapor pressures of a number of fuels determined in this manner are given in Table I and plotted in Figure 4.

GRADUATED-BULB METHOD—The procedure outlined above is time-consuming and requires very careful technic. For this reason the graduated-bulb method was developed because of its greater simplicity of application.

Theoretical Development. If the dissolved gas in the motor fuel may be considered as equivalent to a single component, and the vapor pressure of the gas-free sample is substantially constant for different amounts of fuel vaporized within narrow limits, the following treatment indicates that the gas-free vapor pressure may be readily computed by determining the vapor pressure of the sample at three different vapor space volumes:

Let x = mols of gas dissolved in liquid at zero vapor space
 p = partial pressure of this gas at any vapor space above liquid
 p_0 = partial pressure of corresponding gas at zero vapor space
 P = total pressure on system at any vapor space
 P_0 = total pressure on system at zero vapor space
 P_g = vapor pressure of gas-free sample
 K = Henry's law constant, or proportionality factor between solubility of gas in mols and its partial pressure

By Henry's law

$$x = p_0 K \quad (1)$$

at zero vapor space. If a vapor phase is formed from the liquid sample, the number of mols of gas vaporized equals

$$\frac{pV}{RT} \quad (2)$$

in which V = volume of the vapor phase
 R = gas constant
 T = absolute temperature

A material balance after vapor space V has been formed gives

$$Kp = x - \frac{pV}{RT} \quad (3)$$

Rearranging,

$$p = \frac{xTR}{KTR + V} \quad (4)$$

The total pressure at any vapor space equals the sum of the vapor pressure of the gas-free sample and the partial pressure of the gas, or

$$P = P_g + \frac{xTR}{KTR + V} \quad (5)$$

or

$$(13)$$

$$P = P_0 + \frac{c}{a + V} \quad (6)$$

where a and c are constants, dependent only on temperature for a given sample of fuel. This equation involves three unknowns and can be solved for P_0 if the total pressure is known for three different vapor volumes at a constant temperature. Using subscripts 1, 2, and 3 to indicate experimental data of pressure taken at different vapor spaces,

$$P_1 = P_0 + \frac{c}{a + V_1}$$

$$P_2 = P_0 + \frac{c}{a + V_2}$$

$$P_3 = P_0 + \frac{c}{a + V_3}$$

Eliminating the constants c and a and solving for P_0

$$P_0 = \frac{P_1 V_1 (P_2 - P_3) + P_2 V_2 (P_3 - P_1) + P_3 V_3 (P_1 - P_2)}{V_1 (P_2 - P_3) + V_2 (P_3 - P_1) + V_3 (P_1 - P_2)} \quad (7)$$

This equation can be further simplified by choosing particular values for the vapor volume. If the vapor spaces are in the ratio 1:3:5,

$$P_0 = \frac{2P_1P_3 - P_1P_3 - P_2P_3}{2P_3 - P_3 + P_3} \quad (8)$$

in which P_1 = vapor pressure determined with first vapor space
 P_3 = vapor pressure determined with a vapor space three times that of first one
 P_5 = vapor pressure determined with a vapor space five times that of first determination

The volumes of the vapor spaces should be so chosen that the largest does not exceed 20 or 25 per cent of the liquid volume.

Apparatus. In order to measure readily the vapor pressures of samples of fuel with different vapor spaces, the apparatus shown in Figure 5 was constructed. The graduated glass bulb in which the sample is placed forms the end of one side of a mercury manometer. It is fitted at the top with a two-way offset stopcock, through which the sample is forced into the bulb by mercury displacement. The bulb is so designed and graduated that a minimum dead space exists from the stopcock to the first graduation mark.

Violent agitation of the sample may be obtained by a flattened glass tube which extends up the center of the bulb for its entire length. The flattened part of the stirrer is welded to a round tube which passes through the rubber stopper at the bottom of the bulb and is connected by rubber tubing to the vertical rods connected to the eccentric on the motor. The intensity of agitation can be controlled by the speed of the motor so that the sample attains equilibrium with the vapor very rapidly. The pressure was measured in the usual manner on the mercury manometer.

Procedure. Before running the sample into the bulb, the

mercury was freed from entrapped air by filling the bulb with mercury. The stopcock was then closed and the pressure reduced to "boil out" the air. This process was repeated until the mercury could be lowered from the bulb and the pressure reading would check the barometer within 3 or 5 mm.

The cold sample of gasoline was then flowed under pressure through a three-way cock connected to the charging cock until all lines were cold. Sufficient fuel was run into the bulb to fill it, after which this first sample was discarded. The bulb was charged with the desired sample in the same

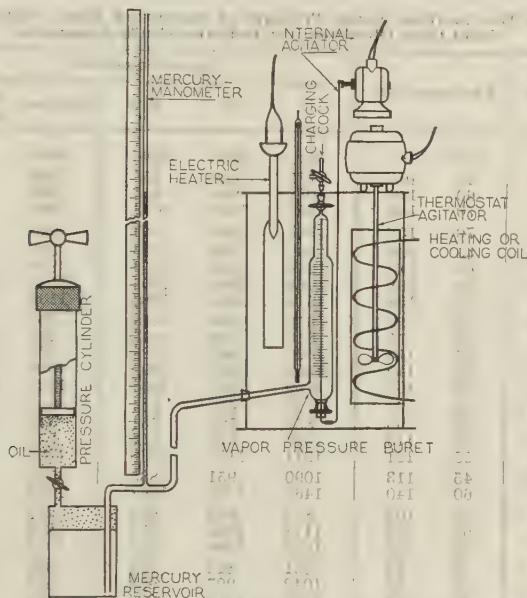


Figure 5—Graduated-Bulb Vapor-Pressure Apparatus for Determining Vapor Pressure of Complex Mixtures at Different Vapor Volumes

manner, while the mercury column was so regulated as to maintain the greatest possible pressure on the sample. The charging cock was then closed and made tight by a mercury seal.

The thermostatically controlled bath was next brought to the desired temperature. The pressure cylinder was so adjusted as to form approximately the desired vapor space in the bulb. The internal agitator was started and kept running until the sample had come to equilibrium. Readings were then taken of the vapor space, mercury level on the manometer scale, and also on the bulb scale. The mercury level was lowered to form a larger vapor space and the same procedure followed until the desired data had been obtained.

Results. Data obtained in this manner are presented in Table II and used to compute the gas-free vapor pressure

according to Equation 8. The resulting dry gas-free vapor pressures as computed by this method are plotted in Figure 4 so that they may be compared with the vapor pressures determined directly on the gas-free dried sample. Since the samples used in the graduated-bulb apparatus were not dried but were saturated with water, the vapor pressure of water was subtracted from that of the fuel sample in order to make possible the direct comparison of the results obtained with the two methods. These results indicate that the gas-free vapor pressure may be determined by either method.

Table II—Gas-Free Vapor Pressure of Saturated Fuels, Calculated from Data Obtained in Graduated-Bulb Apparatus

FUEL	TEMPERATURE		VAPOR PRESSURE				
			P_1	P_2	P_3	Gas-free	Dry and gas-free
	° C.	° F.	<i>Mm.</i>	<i>Mm.</i>	<i>Mm.</i>	<i>Mm.</i>	<i>Mm.</i>
2	40	104	775	629	558	353	298
	60	140	1072	926	855	650	501
	70	158	1258	1120	1053	860	627
35	70	158	1377	1240	1183	1045	812
37	40	104	869	786	735	521	466
	60	140	1246	1169	1117	849	700
	70	158	1468	1360	1305	1136	903
	70	158	1512	1432	1380	1135	902
38	15	59	653	494	418	203	190
	25	77	810	688	613	295	272
	45	113	1020	863	788	575	504
	65	149	1500	1365	1290	1028	741
	75	167	1750	1632	1566	1332	1044
54	25	77	725	656	614	391	368
	35	95	857	793	751	549	507
	45	113	1023	959	918	750	679
	55	131	1211	1157	1128	1032	915
57	45	113	1090	951	885	700	629
	60	140	1461	1330	1264	1064	915
58	40	104	813	688	630	472	417
	60	140	1118	1035	971	809	660
	70	158	1385	1266	1205	1016	783
72	5	41	861	813	774	397	390
	15	59	1042	997	960	581	568
75	45	113	1189	1135	1102	965	894
	55	131	1477	1428	1398	1273	1155
1041	60	140	1277	1197	1148	944	795
	70	158	1513	1405	1350	1181	948
1042	40	104	1108	960	900	758	703
	60	140	1602	1462	1387	1139	990
	70	158	1923	1786	1712	1464	1231
1043	40	104	1289	1152	1082	866	811
	60	140	1786	1655	1580	1304	1155
	70	158	2118	1982	1905	1627	1394
1044	40	104	876	747	684	501	446
	60	140	1277	1152	1090	906	757
	70	158	1550	1430	1366	1156	923

The gas-free vapor pressures of the samples saturated with water were used in determining the initial boiling point of the continuous vaporization curves, as indicated in Figure 6 and also in Figure 17 of Part I of this series (4).

GAS-FREE VAPOR PRESSURE FROM A. S. T. M. DISTILLATION—It has been suggested that the temperature at which the fuel exerts 1 atmosphere vapor pressure is equal to that of the 10 per cent point on the A. S. T. M. distillation curve when corrected for loss, and that the temperature of the liquid

in the flask when vapor is first evolved is also the same as that of the 10 per cent point. For this reason these fuels were carefully distilled according to the A. S. T. M. method with the addition of a thermocouple in the liquid. The results (Table III) indicate that these assumptions are not justified except as a rough approximation.

RELATION OF GAS-FREE VAPOR PRESSURE TO VAPOR LOCK—A summary of most of the road and laboratory engine tests is included in Table IV with a comparison of the different vapor-pressure determinations. Although the agreement between the temperature at which vapor lock is observed and that at which the gas-free fuel exerts 1 atmosphere pressure is fairly satisfactory, better correlation is evident with vapor pressure determined with a specified ratio between the volume of vapor and liquid phases. These vapor pressures were determined in the graduated-bulb apparatus in the manner described.

Actual Vapor Pressure

Since trouble due to vapor lock was first noticed when the volume of vapor passing through the carburetor was about twice that of the liquid, it is to be expected that vapor pressure taken with this vapor-liquid ratio would coincide closely with the first evidence of possible vapor lock. The temperature at which serious vapor lock was observed was frequently much higher or lower than that at which the gas-free vapor pressure was atmospheric and corresponded more closely to the temperature at which atmospheric pressure was observed with a vapor-liquid volume ratio of about 5 or 6, or that at which atmospheric pressure was observed in the Reid vapor-pressure bomb.

Table III—Gas-Free Vapor Pressure, Estimated from A. S. T. M. Distillation

FUEL	TEMP. AT WHICH DRY GAS-FREE VAPOR PRESSURE IS 740 MM.	A. S. T. M. 10% POINT COR. FOR LOSS	TEMP. OF LIQUID IN FLASK WHEN VAPORIZATION STARTED
	° F.	° F.	° F.
2	172	163	170
35	148	137	148
35 ^a	138	...	...
37	141	130	140
38	141	146	142
48	111	112	109
54	118	133	124
57	124	121	116
58	150	136	145
68	104	113	95
75	94	102	96
1041	140	130	141
1042	110	117	103
1043	97	135	105
1044	140	126	137

^a Sample removed from vacuum tank after absorbing bubbles of vapor formed in fuel line to carburetor.

IN GRADUATED-BULB APPARATUS—These results appear logical because the dissolved gases and water in the fuel must

Table IV—Summary of Vapor-Lock Tests

FUEL	LOWEST TEMP. AT WHICH VAPORIZATION INDICATED	LOWEST A. S. T. M. TEMP. 10% AT WHICH VAPOR LOCK OBSD. FOR LOSS		COMPOSITION BY WEIGHT				TEMPERATURE FOR ATMOSPHERIC VAPOR PRESSURE DETERMINED BY METHOD INDICATED				REID VAPOR PRESSURE AT 100° F.	Lbs. per sq. in.	
		° F.	° F.	Propane Per cent	Butane Per cent	Pentane Per cent	Beistle ° F.	Reid ° F.	GAS-FREE		VAPOR SPACE LIQUID SPACE 2 = 1			
									Satd.	Dry				
2	145	154	163											
35	145 (OK)	150	137	0.2	4.7	16.8		156	149	172	145		6.2	
35 V	130	137	130	0.35	5.75	16.7		147	130	146	138		6.75	
37	125	135	130	0.51	8.1	17.2		132	129	138	122		8.2	
38	120	132	146					129	126	141	122		8.6	
48	100	106	112	0.3	3.8	39.6		130	108	125	141			
54	160 (OK)	133	133	1.15	5.2	9.0		102	103	111			12.5	
55	87 R	123 R	112	0.75	9.6	15.7		120	109	118			14	
	83 L	101 L							103					
57	110	118	114	None	2.2	38.2		111	117	124				
58	138	160	136	0.3	10.3	12.3		122	152	133	113		9.25	
60	156 (OK)	156	156					158	148	170	149		6.4	
65		86	89										6.1	
68	85	113	113	0.11	5.51	12.47		112	114				11.2	
75	80 L	87 L	102	0.035	5.61			103						
	108 R	118 R								104				
76	106		118					159						
1025	176 (OK)		182	Trace	2.5	5.1		149						
1027	85	88	99	8.7	8.5	37		130						
1028	168 (OK)	130	150	None	4.5	7.4		145						
1029	120	140 R	142	Trace	1.4	13.8		147	148					
1030	147 (OK)		146	1.62	6.0	17.1		140					6.6	
1033	150 (OK)		193	0.6	2.0									
1034	105	125	145											
1035	107	120	121	2.0	6.9	7.0		126					9.2	
1036	172 (OK)		154											
1037	150 (OK)		180	Trace	1.5	4.0		133						
1041	133	145	130	0.2	7.3	21.6		133					8.5	
1042	110	117	117	Trace	10.3			114	102	140	122		11.75	
1043	104	112	135	2.3	1.5			107	92	97	102		13.1	
1044	121	144	127	0.04	3.6			133	126	140	121		8.2	

(OK) Indicates no trouble at indicated temperature.

R indicates road-tests data when differing from laboratory.

L indicates engine test in laboratory when differing from road test.

V indicates sample removed from vacuum tank after absorbing bubbles of vapor formed in fuel line to carburetor.

have some influence on the vapor pressure and on the tendency to cause vapor lock. In taking the vapor pressure in the graduated-bulb apparatus, the sample is used as received. No moisture or dissolved gas is removed before making the vapor-pressure measurements. Furthermore, this test in which the vapor pressure is taken with different vapor-liquid volume ratios can be used as a fairly satisfactory check of the efficiency of a particular fuel system in regard to vapor lock. There is direct evidence that different types of carburetors and fuel systems vapor-lock at temperatures corresponding to atmospheric vapor pressure of the fuel with different vapor-liquid volume ratios.

IN REID VAPOR-PRESSURE BOMB—The Reid vapor-pressure method has now been adopted by the Interstate Com-

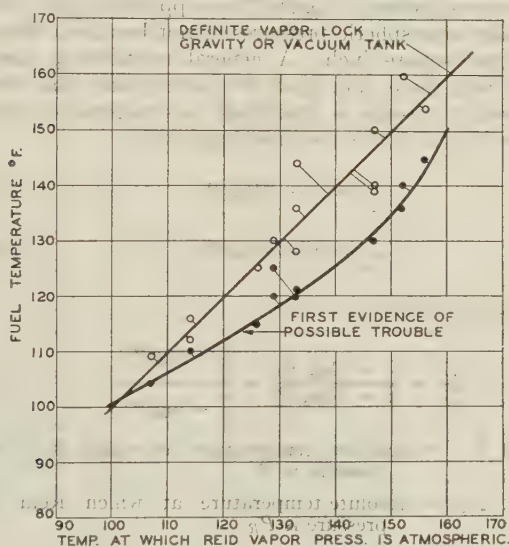


Figure 6—Fuel Temperature at Which Vapor Lock Was Observed Plotted as a Function of Temperature at Which Reid Vapor Pressure Is Equal to Atmospheric Pressure

merce Commission and as a tentative standard of the American Society for Testing Materials. Because it promises to be the method most widely used by the industry, a satisfactory relationship between the Reid vapor pressure and temperature at which the fuel may cause vapor lock is extremely desirable. For this reason the experimental results have been plotted in Figures 6 and 7 to determine if such a relationship may be found. Scattering of the points is within the limits of accuracy with which the probable maximum temperature of the gasoline can be estimated. The temperature at which the Reid vapor pressure is equal to atmospheric pressure corresponds rather closely to that at which serious vapor lock is first observed as indicated in Figure 6:

However, it is not convenient to determine the temperature at which the Reid vapor pressure is atmospheric but rather to determine the vapor pressure at some particular temperature. Since the vapor-pressure curve of hydrocarbons may be represented approximately by straight lines if the log of the pressure is plotted against the reciprocal of the temperature, the same form of plot might be applicable to the Reid vapor pressure of fuels. This fact suggested the plot shown in Figure 7 in which the log of the absolute temperature at which the fuel gives various degrees of vapor-lock trouble is plotted as a function of the reciprocal of the Reid vapor pressure in pounds per square inch at 100° F., since this is the standard temperature for making Reid vapor-pressure determinations.

The curves shown in Figure 7 are applicable only to fuels used under atmospheric pressures of not less than about 14 pounds per square inch. A general relationship may be derived from these data upon the assumption that the log of the vapor pressure is practically a straight-line function of the reciprocal of the absolute temperature,

$$\frac{1}{T} = a - b \log P \quad (9)$$

$$\frac{1}{T_R} = a - b \log P_R \quad (10)$$

Dividing (10) by (9)

$$\frac{T}{T_R} = \frac{a - b \log P_R}{a - b \log P} = \frac{\frac{a}{b} - \log P_R}{\frac{a}{b} - \log P} \quad (11)$$

in which T = absolute temperature at which Reid vapor pressure is P

T_R = absolute temperature at which Reid vapor pressure is P_R

a and b = constants

Since the two equations apply to the same fuel in any particular case, a and b are identical in Equations 9 and 10. Therefore, Equation 11 may be written

$$\frac{T}{T_R} = \frac{A - \log P_R}{A - \log P} \quad (12)$$

The numerical value of A in Equation 12 may be readily determined from data plotted in Figure 7. The most reliable vapor-lock data were obtained with those fuels causing trouble at about 120° F. which showed an average Reid vapor pressure at 100° F. of about 10 pounds per square inch. The tests were conducted under atmospheric pressures of about 14.5 pounds per square inch in most cases and the Reid vapor pressures were not corrected for the vapor pressure of the dissolved water. As shown in the discussion of gas-free vapor pressure, the samples of fuel were saturated

with water and the vapor pressure of the dry fuel can be readily computed by simply subtracting the vapor pressure of water at the required temperature.

The numerical value of A for saturated vapor pressures was obtained by substituting the saturated vapor pressures as recorded in the tables and solving for A

$$\frac{580}{560} = \frac{A - \log 10}{A - \log 14.5} = \frac{A - 1}{A - 1.161}$$

$$580A - 674 = 560A - 560$$

$$A_{\text{satd.}} = 5.7 \text{ for saturated Reid vapor pressures}$$

The numerical value of A for dry vapor pressures, as computed by applying the recommended corrections to the observed Reid vapor pressures, was obtained by subtracting the vapor pressure of water from that of the saturated samples and making a similar substitution in Equation 12.

$$\frac{580}{560} = \frac{A - \log (10 - 0.94)}{A - \log (14.5 - 1.7)} = \frac{A - 0.957}{A - 1.1072}$$

$$580A - 640 = 560A - 536$$

$$A_{\text{dry}} = 5.2 \text{ for dry Reid vapor pressures}$$

These values of A are based on direct determination of vapor lock in engine tests which indicated that the fuel might cause vapor-lock trouble when its Reid vapor pressure equaled or exceeded the pressure on the fuel. All motor fuels appear to be saturated with water under conditions of actual use, and these values for $A_{\text{satd.}}$ and A_{dry} are equally applicable under such conditions. The dashed line in Figure 7 is the curve indicated by these values for A in Equation 12 assuming an "atmospheric" pressure, or pressure on the fuel of 14.5 pounds per square inch.

Since the standard temperature for taking Reid vapor pressures is 100° F., the use of Equation 12 may be somewhat simplified, as indicated for Equation 13, by taking a value of 5.167 for A_{dry} so that the denominator reduces to 4 for 14.7 pounds per square inch atmospheric pressure when using dry Reid vapor pressures as determined at 100° F.

$$t = 560 \frac{5.167 - \log P}{5.167 - \log P_A} - 460 \quad (13)$$

where t = temperature, ° F., above which vapor lock may be expected when fuel is under a pressure of P_A pounds per square inch absolute

P = Reid vapor pressure, in pounds per square inch, of dry fuel at 100° F.

P_A = atmospheric pressure

$$t = 140 (5.167 - \log P) - 460 \quad (14)$$

where t = temperature, ° F., above which vapor lock may occur under a pressure of 14.7 pounds per square inch

P = Reid vapor pressure in pounds per square inch, of dry fuel at 100° F.

SUMMARY—These relationships are not so accurate as that between the vapor-locking temperature and the temperature at which the vapor pressure is atmospheric with a vapor-liquid volume ratio of 2, 4, or 6, depending upon the degree of vapor lock and the efficiency of the fuel system under discussion. They are, however, more satisfactory than any direct relationship to the gas-free vapor pressure or any single point on the A. S. T. M. distillation curve.

The great convenience of a direct relationship between the temperature at which a fuel might vapor-lock and the 10 per cent point on the A. S. T. M. distillation may cause unwarranted use of the 10 per cent point as an indication of vapor-locking tendency. Although fairly satisfactory in the case of many representative motor fuels, it may frequently introduce an error of 20° F. or more.

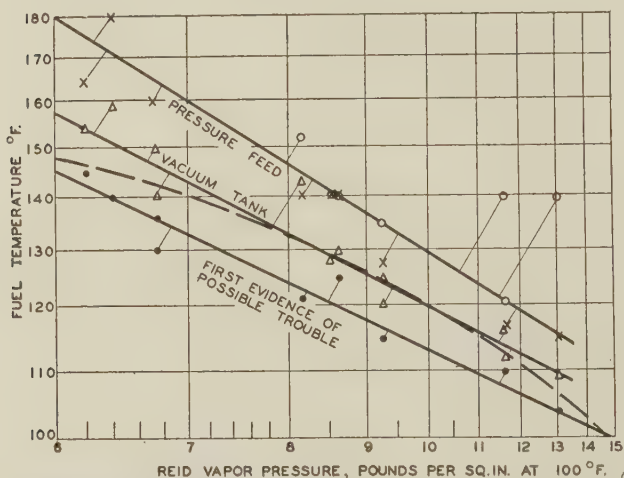


Figure 7—Log of Absolute Temperature of Fuel at Which Vapor Lock Was Observed Plotted as a Function of Reciprocal of Reid Vapor Pressure

Probable Maximum Fuel Temperature Dependent upon Atmospheric Temperature

For an intelligent use of the relationship reported between the vapor-pressure characteristics and temperature at which a fuel will probably cause trouble due to vapor lock, the maximum fuel temperatures found under actual driving conditions must be known with reasonable precision. Different cars operate at different fuel temperatures and it is obviously impossible to consider in this discussion individual motor-car characteristics. The car used in the road tests is a notorious offender in regard to vapor lock and undoubtedly heats the liquid fuel to temperatures as high as are ever encountered under like conditions. The maximum temperatures at different places in the fuel system, and under different driving conditions, are reported in full elsewhere (3).

It was found that the fuel temperature never exceeded $100 + \frac{1}{2}$ atmospheric temperature ($^{\circ}$ F.) when driving at 40 miles per hour or more. Higher temperatures were obtained only when speed was reduced to 30 miles per hour or less from high speeds. The highest temperature recorded when gasoline was known to be in the bowl of the carburetor was 184° F. with an atmospheric temperature of 84° F. After the car speed had been suddenly stopped from a sustained speed of 65 miles per hour, temperatures of over 220° F. were recorded for the fuel in the line to the carburetor. But some doubt may be expressed as to the actual presence of much liquid fuel in the line under these conditions. On other cars temperatures as high as 180° F. have been observed under severe conditions. These temperatures probably represent the maximum temperatures to be encountered even under unfavorable conditions. Even so a straight line represented by the equation:

$$\text{Fuel temperature} = 100 + \frac{1}{2} \text{atmospheric temperature} \quad (15)$$

($^{\circ}$ F.)

appears to represent adequately the average maximum fuel temperatures.

Conclusion

The tendency of a fuel to cause trouble due to vapor lock is most accurately indicated by the vapor pressure of the fuel "as used" measured with a vapor-liquid volume ratio equal to that at which trouble is experienced in the particular fuel system under consideration. Usually this ratio is not less than 4, and the vapor pressure as determined in the Reid bomb may be used with entirely satisfactory results. From the determination of vapor pressure in the Reid bomb at one temperature Equation 12 or 14 may be used to determine the fuel temperature above which a fuel may vapor-lock.

A more convenient, but less reliable, indication of the temperature above which vapor lock may be expected is the 10 per cent point on the A. S. T. M. distillation corrected for loss. This relation combined with that between the atmospheric temperature and average probable maximum fuel temperature indicates the following expression as placing a minimum on the 10 per cent temperature for fuels used in modern motor cars:

$$\text{Minimum A. S. T. M. 10 per cent} = 100 + \frac{1}{2} \text{average atmospheric temperature } (^{\circ} \text{ F.})$$

This relation was used in setting the minimum 10 per cent points recommended in Part IV.

The most effective means of eliminating vapor lock is by proper design of the fuel system. As car manufacturers respond to this requirement, fuels of lower 10 per cent points and higher vapor pressures giving more easy starting in cold weather may be used.

Acknowledgment

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